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Study of Water Entry of High-Speed Projectile

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Abstract

For the purpose to investigate the physical process during the command destruction of space rocket by means of Conical Shaped Charge (CSC), a series of fundamental experiments which configure each part of the actual processes were carried out. In the first experiments, CSC was fired into water filled in polyvinyl chloride pipe to obtain the shape and velocity of the jet. In the next experiments, same CSC was fired into water-filled steel tank to measure pressure in the water and structural response of tank. In the third series of experiments, the 12.7mm AP bullet was shot into the partially water-filled and pressurized tank to investigate fracture behavior. This paper presents the summary of the results of these experiments with some numerical simulation results.

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Keywords: Command destruction, Conical Shaped Charge, Water entry , Water-filled tank, Hydrodynamic RAM

1. Introduction

Linear Shaped Charge (LSC) and Conical Shaped Charge (CSC) are installed in the command destruct circuit on the space rockets. They would be activated in emergency to destruct the rocket in compliance with the range safety requirement. So the comprehension of the physical process of the destruction is very important in building space rocket. This study has been proceeded in this purpose, assuming liquid-propellant space rocket with CSC command destruction system.

Whole process of the command destruction by CSC is highly complicated. It shall be as: The CSC will be activated to generate the explosively formed metal jet. The jet perforates the tank-wall and comes into the liquid propellant. High-speed jet penetrates into propellant produce shock wave and also its momentum is transferred to the liquid, and the tank-wall is subjected to pressure in conjunction with contribution of potential chemical reaction and finally it will be fractured. Hydrodynamic RAM (HRAM) is the phenomenon that when a high-velocity projectile penetrates a liquid-filled container, momentum and kinetic energy of the projectile are transferred through the fluid to the container causing excessive damage. So it is quite important with aircraft in estimating damage of fuel-tank by attack by fragments outside. Numerous researches have been carried out to understand the HRAM, though undeformable projectile is used in most of them. For instance, Nishida and Tanaka [1] investigated the crack and the perforation limit velocities of thin-walled aluminum alloy tubes impacted by spherical steel projectiles at impact velocities ranging from 40-200m/s and found that filling the tubes with water decreased wall strength. Varas et al. [2,3] measured pressure in water and dynamic strain of aluminum tube subjected to impact of steel sphere, and they also showed that the results were successfully simulated using LS-DYNA. On the other hand, there are relatively few works performed for liquid-entry of CSC jet. White et al. [4] performed experimental study of shaped charge jet penetration using seven common liquids including water and examined the difference of penetration resistance. Andersson et al. [5] investigated the effect of the radius of penetration channel filling water on the penetration

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depth into the steel target. From the computer simulation, the importance to take into account the compressibility, shock wave formation in water and target material motion has been recognized.

For the simplicity and for the purpose of quantity analysis, we divided the actual process into four parts and a series of fundamental experiments, Experiment-1 through Experiment-3 shown in Table 1, have been performed, where two types of CSCs were prepared which are different in cone angle of liner. Experiment-1 was performed to investigate basic properties of jet in order to use the validation of numerical simulation, such as shape, velocity and penetration depth into the target. Experiment-2 was performed to investigate the phenomenon of jet-entry into water using larger tank. Pressure in water, dynamic strain of water-filled tank obtained by these test are presented. Experiment-3 was performed to observe the fracture behavior of liquid-filled and pressurized tank, which simulates the condition of rocket tank better. In this experiment, the 12.7mm armor piercing shot and shell (AP) bullet was shot into the water-filled tank to see how it breaks instead of CSC jet. This paper presents the results of experiments mentioned above and also some results of numerical simulation.

Table 1. Physical components of command destruction and fundamental experiments

Event	CSC jet formation	Jet (Projectile) entry into Fluid	Structural response (HRAM)	(Chemical reaction)
Command Destruction	○	○	○	○
Experiment 1	○	○	-	-
Experiment 2	○	○	△ (Elastic)	-
Experiment 3	-	○	○ (Fracture)	-

2. Experimental Setup

Fig.1 shows the schematic drawing and an example of picture of the Experiment-1 setup. The purpose of this experiment is to obtain the basic properties of CSC jet by observation of the shape and the measurement of its velocity. The apparatus was vertically set and the CSC is put on the top of tube made of polyvinyl chloride pipe. The stand-off (distance between the face of CSC and water surface) is 50mm in all the cases. Water was filled inside the polyvinyl chloride pipe of 152mm in inside diameter and 6.5mm in wall-thickness. Also the experiments without this water pipe were conducted to represent the free-flight of the jet. The shape of the jet was visualized by means of a pair of flash x-radiography systems in which the exposure time is 20ns and the output voltage 300kV. Break papers were placed at various locations along the centerlines, including interfaces of stack of mild steel plates to capture the jet tip.

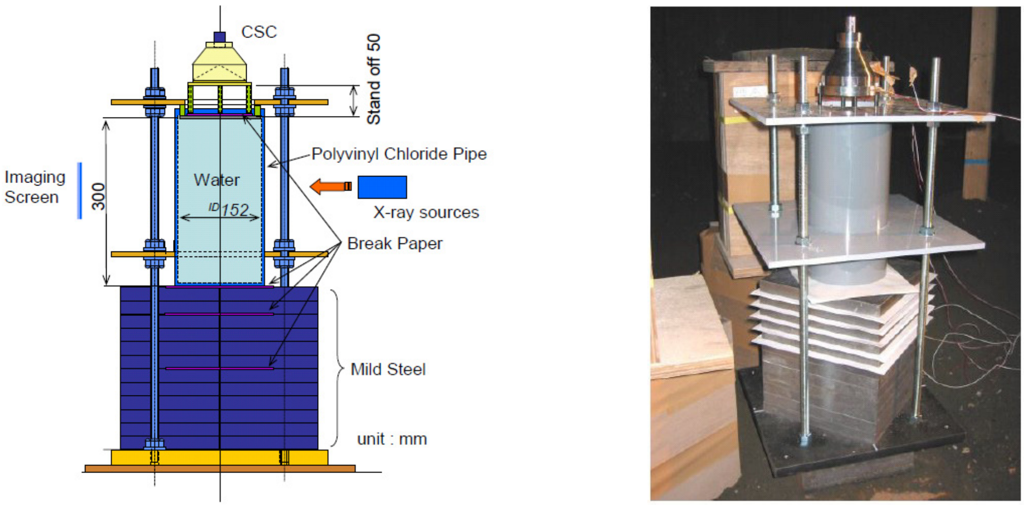

Fig.1. Schematic drawing and an example of the Experiment-1 setup

In the Experiment-2, the thick steel-tank with large diameter was used to measure the pressure propagation in the water and elastic response of the tank-wall. The pressure in the water was measured with tourmaline sensors (Model 138A10. Maximum range is 69MPa). Stack of mild steel plates were similarly set at the bottom of the tank to find out the influence of diameter of water channel on penetration depth. Fig.2 shows the sketch and an example of picture of the experimental setup. The CSC was put on the lid made of steel and the stand-off was also 50mm. The CSC used for both Experiment-1 and Experiment-2 is as shown in Fig.3. Two types of CSCs, with the cone angle of 120°or 90°, were prepared. The thickness of liner is 2.5mm and the explosive is C4 with filling density of 1.4g/cc.

In the Experiment-3, the 12.7mm AP bullet was used instead of CSC jet giving priority to the easiness of the observation of fracture behavior than obtaining large impact velocity. The bullet-diameter of 12.7mm was selected to model the CSC jet, and the use of the bullet enabled us to observe the phenomena with high-speed camera. Schematic drawing of this experiment and an example of setup was as shown in Fig.4. In this experiment, the target was partially water-filled and pressurized tank made of thin stainless steel or aluminum alloy, which were also selected to model general rocket tanks. The velocity of bullet was measured by the signals from two break papers placed in front of the tank, and response of the tank was studied by strain gauges and a high-speed camera.

All these experiments were conducted in the trench of Chugoku-kayaku Corporation, and were fully controlled from the cage outside for the safety.

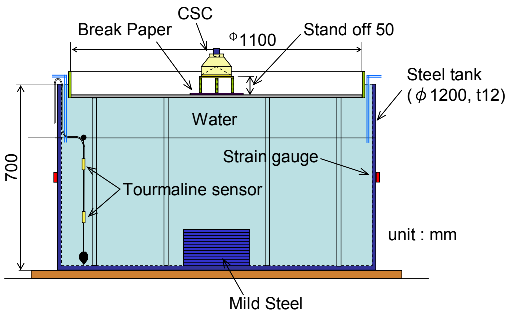

Fig.2. Schematic drawing and an example of the Experiment-2 setup

Fig.3. Conical Shaped Charge used for the Experiment-1 and Experiment-2

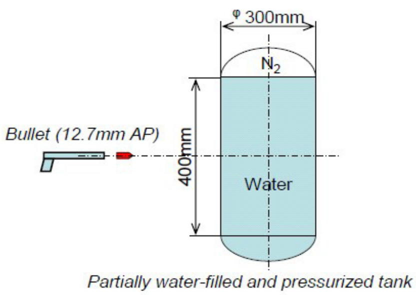

Fig.4. Schematic drawing and an example of the Experiment-3 setup

3. Computational Method

The first step to develop numerical simulation techniques is to simulate the jet formation process in air and in water, and the results of Experiment-1 were referred for the purpose of comparison. A hydrocode: AUTODYN [6] was applied for the numerical simulation. Calculation models were made in the axisymmetric geometry and the multiple material Eulerian processor was utilized for all the parts included in the system. The simulations were performed using the material models as shown in Table 2 from AUTODYN material library except the density of C4. The polyvinyl chloride pipe was ignored in the simulation and the standard atmospheric pressure was considered as an initial state.

Table 2. Material models

Material	Equation of state	Strength model
C4	JWL	N/A
Aluminum (Casing)	Shock	von Mises
Copper (Liner)	Shock	Steinberg-Guinan
Water	Shock	N/A
Air	Ideal gas	N/A

4. Results

4.1. Experiment-1

Figures 5 and Fig.6 show the comparison of shape of jet obtained by X-radiography systems and numerical simulation at the indicated time from ignition. In the simulation results, the contours indicate the velocity distribution in the metal jet. It is recognized that numerical simulation reproduced the experimental results according to the shape of jet. In Fig.6, it is interesting that the bow-shaped materials clearly seen at the tip of metal jet in both of X-ray image and numerical simulation.

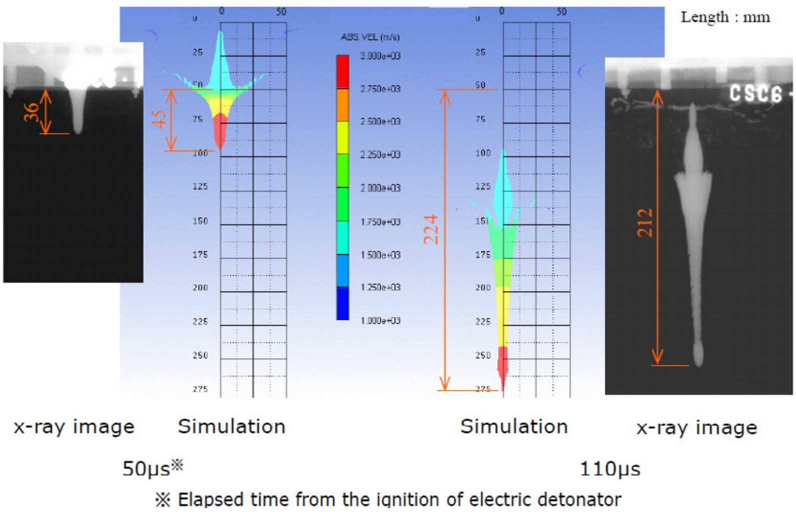

Fig.5. Flash X-ray photographs and simulated jets (cone angle 120°, free shot)

Fig.7 shows the relation between the location and time obtained by the output from break papers and flash X-ray images. Circle marks are for free flight in the air and filled diamond or triangle marks for in the water penetration case. It should be noted that there is little difference between the results of water penetration, the Experiment-1 (denoted as Water (R76)) and the results of Experimen-2 (denoted as Water (R600)), and it means that the motion of jet is affected by only water at the vicinity of the projectile. So the properties of CSC jet, shapes and velocities, obtained in small-diameter water tube would not be special. The solid line and broken line means the simulation results, and it seems they could trace the experimental results with enough accuracy.

The tip velocity of jet was calculated using the data shown in Fig.7, and is shown in Fig.8 with the simulation results. During the penetration into the water, the jet loses its velocity much more than in the air, both in the manner of constant deceleration. Table 3 showed the measured velocity of jet and penetration velocity by theory assuming steady flow [7]. Experimental plots give smaller values than the theoretical velocity by energy dissipation and finite length of the metal jet. Fig.9 shows the experimental results of residual penetration into the accepter made of mild steel. It is seen that both types of CSC have almost same ability of penetration. The jet formed by CSC with 120° cone angle has smaller velocity and larger mass, on the other hand the CSC with 90°cone angle has comparably larger velocity and smaller mass.

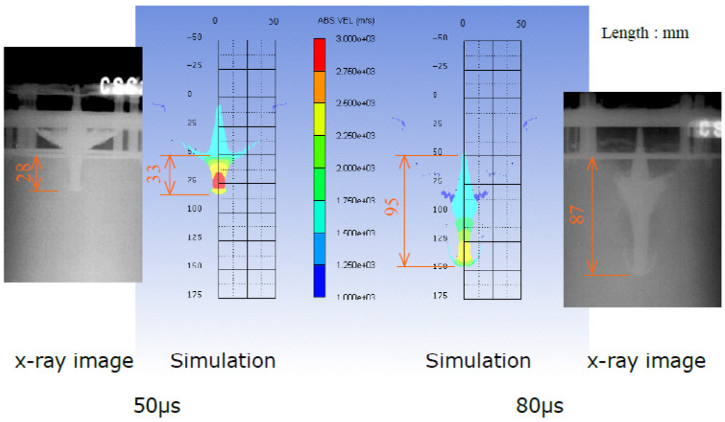

Fig.6. Flash X-ray photographs and simulated jets (cone angle 120°, shot into the water)

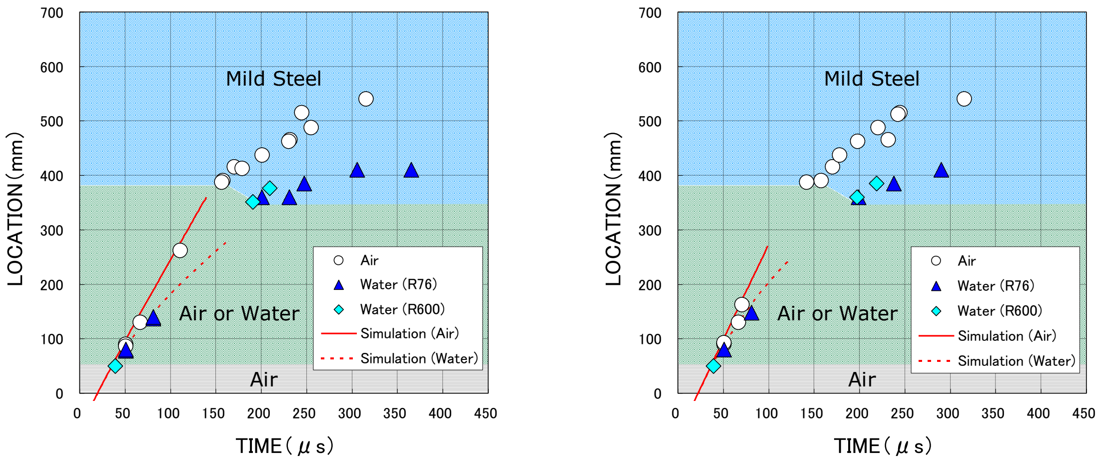

Fig.7. Time history of location of the tip jet for (a) cone angle 120 degree and (b) cone angle 90 degree

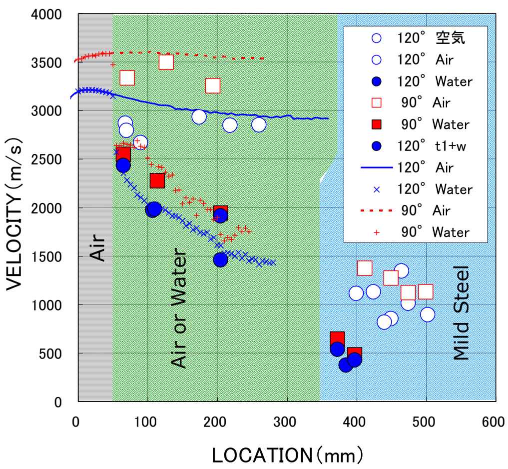

Fig.8. Velocity of the tip jet

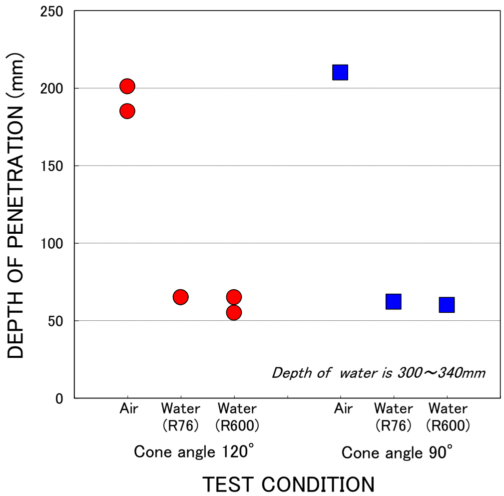

Fig.9. Depth of penetration into steel

Table 3. Velocity of projectile and penetration velocity

Cone angle (*deg.*)	Velocity of CSC jet (*m/s*)	Penetraion velocity Air→Water	Air→Steel
120	2900	2608	1543
90	3400	3058	1809

4.2. Experiment-2

The pressure in the water was caught reasonably by tourmaline sensors, located at points A and C as shown in Fig.10, though the sensors as point B didn't work well in this case. The pressure at point A began to rise at around 0.36ms after ignition up to about 40MPa and its duration was about 0.4ms. The pressure at point C responded later time and had smaller peak though it contained high frequency components much. Fig.11 shows an example of strain of tank-wall in the case of setting the CSC with 120°cone angle at the center of the lid. The dominant response began at about 0.4ms in all the locations and the maximum value show 2,000 to 3,000με. Following these responses, the tendency of damped free vibrations was seen. The first natural period of tank-wall, when it is assumed as ring and considering pure radial vibration mode, is 0.75ms and seems to correspond to the period of the oscillations shown in Fig.11. These features indicate that the tank-wall responded to the shock pressure as shown in Fig.10.

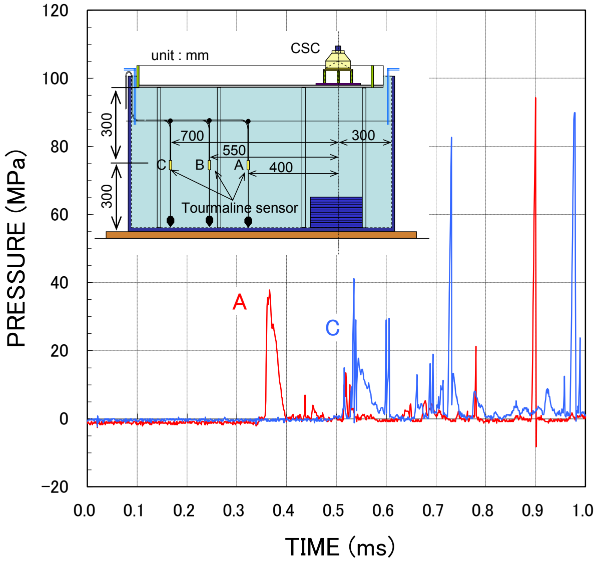

Fig.10. An example of time history of pressure in the water

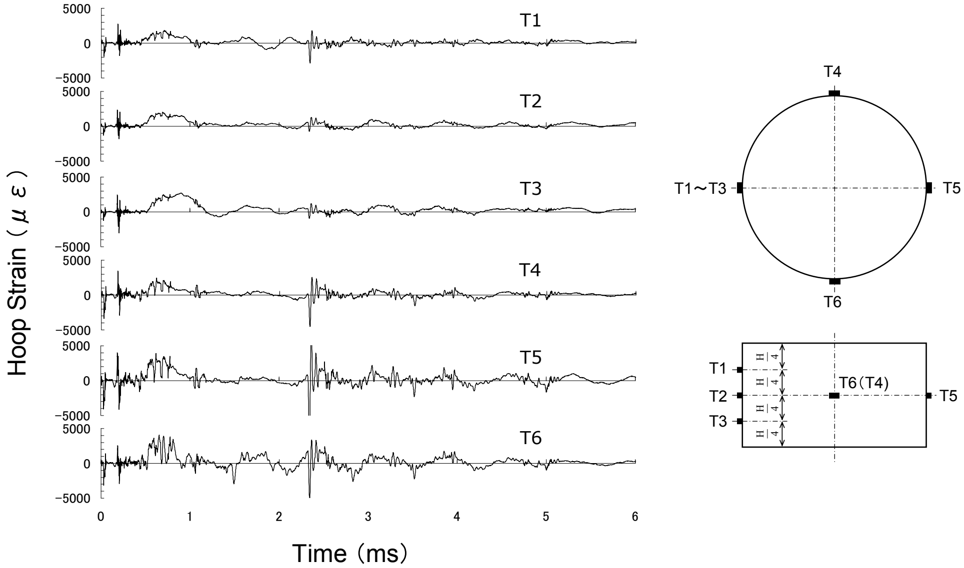

Fig.11. Time history of strain on the water-filled tank

4.3. Experiment-3

Table 3 summarizes results of the Experiment-3. The velocity of bullet was around 850m/s, in average, much smaller than the velocity of CSC projectile. In all the cases, it merely perforated on entry surface of the tank. On the other hand, two types of damage were observed on the exit surface, merely perforation or the burst type fracture. The burst type fracture was observed only in the water-filled tank. An example of the snaps obtained by high-speed camera on the exit surface of the water-filled tank is shown in Fig.12. In this case, it was recognized that the bullet was somehow inclined before it reached to exit of the tank, and the cracking of the tank was urged by the exit of bullet. Varas et al. [1] reported similar experimental results that the deformation on the exit wall is larger than the entry side. Such difference might be occurred by the existence of pre-stress in the tank-wall caused by the shock wave and the subsequent loading by the water due to momentum transfer from the projectile though the quantitative evaluation is required in the future.

Table 4. Summary of results of the Experiment-3

Test ID	Material of tank	Bullet velocity (m/s)	Wall thickness (mm)	Pressure (MPa)	Water height (%)	Damage of tank	
						Entry side	Exit side
1	SUS304	858	0.8	0.6	-	Perforation	Perforation
2	SUS304	852	0.8	1.0	-	Perforation	Perforation
3	SUS304	854	0.8	1.3	90	Perforation	Burst
4	A5052	839	2.0	1.0	-	Perforation	Perforation
5	A5052	865	2.0	1.3	90	Perforation	Burst
6	A5052	873	2.0	1.3	95	Perforation	Burst

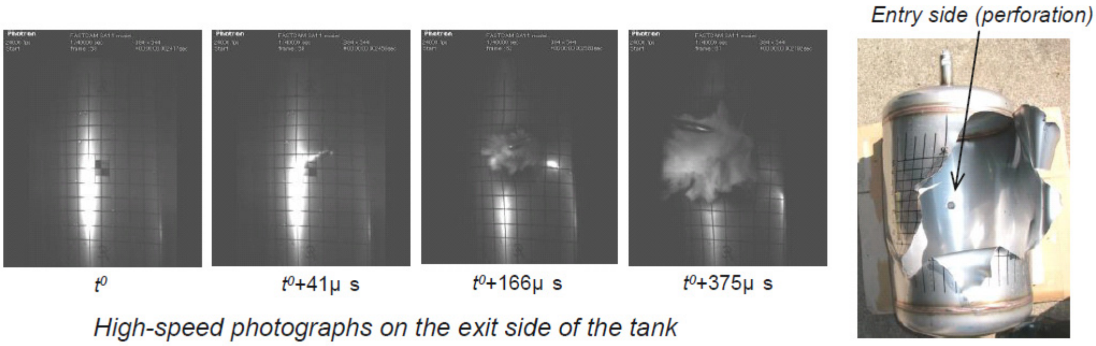

Fig.12. An example of the result of Experiment-3 (Test ID 3)

5. Conclusions

The phenomenon of water entry of high-speed projectile was studied through a series of impact tests. In the first two setups of the experiment, jets formed by CSC were shot into water and its shape and velocity were obtained by means of flash x-radiography systems and break papers. It was recognized that the computational techniques have capability to simulate the phenomenon, though some instability problems in calculation still remain. Also, the time history of pressure in water and strain of water-filled tank due to shock wave were obtained. These data would be able to be utilized for further consideration of HRAM phenomenon. In the third setup of experiment, the 12.7mm AP bullet was shot into the water-filled and pressurized tank and distinctive feature of fracture was observed. Numerical simulation of these experiments is also future work.

In addition, development of a model to simulate mixing and burning process of propellant, fuel and oxidizer, which leads to potential explosion still remains for future work to comprehend the command destruction process and configure space rocket design tool.

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